Origin of the Slow Wave in a Magnetorheological Slurry

In Ref. [1] the propagation of a longitudinal slow mode parallel to an applied magnetic field has been observed in a magneto-rheological slurry. This mode has been discussed in terms of a Biot slow compressional wave as it is found in porous fluid-saturated media [1-3]. The slow mode described in ref. 1 is only observed in the presence of an external magnetic field. This feature all by itself renders a description in terms of a Biot slow wave [4] impossible, since the latter is also expected to occur in any fluid-saturated porous medium in the absence of an external magnetic field. The previous Comment [2] missed this crucial point.

Here we propose a completely different physical mechanism for the origin of this slow mode, namely a wave propagating along the chains or columnar structures formed by the suspended particles that was analyzed previously by the present authors in the context of ferrofluids [5]. As it is clear from Ref. [3] no shear wave component was involved in the experiments in Ref. 1; the formation of separate columns in a field [1,3] is also unfavorable for the presence of a Biot slow wave. Thus what one is looking for is a mechanism specific for materials consisting of magnetic particles suspended in a carrier fluid.

The particles used for the experiments described in Refs. [1,3] are large ($\sim 10\,\mu m$) and thus a magneto-rheological fluid results. If smaller magnetic monodomain particles ($\sim 10\,nm$) are suspended in a carrier fluid, a 'ferrofluid' results [6].

Triggered by the observation of an anisotropy in the velocity of ultrasound in ferrofluids [7], we analyzed the influence of non-hydrodynamic degrees of freedom on sound propagation in 'ferrofluids' [5]. This extension appeared to be necessary since in the strictly hydrodynamic limit the sound velocity must be isotropic in the long wavelength limit. As it turns out [5], the relevant additional macroscopic variables (that is, variables slowly relaxing in the long wavelength limit) are the magnitude of the magnetization density m and the average velocity w of the ferrofluid particles relative to the carrier fluid.

These two variables characterize macroscopically the internal chain motion in an external magnetic field in such a system. Their influence gives rise to two important physical consequences. The first is the anisotropy of the ultrasound velocity. And the second one is the occurrence of a slow mode with a dispersion relation of the type

$$\omega_{1,2} = \frac{i}{2}\left(\frac{\psi}{\rho_f} + \frac{1}{\tau_m}\right) \pm \left[\frac{\chi\, m_0^2}{\rho_f}\, k_z^2 - \frac{1}{4}\left(\frac{\psi}{\rho_f} - \frac{1}{\tau_m}\right)^2\right]^{1/2}, \qquad (1)$$

where k_z is the component of the wave vector along the direction of the external magnetic field $\mathbf{H}$. In the limit $k_z \to 0$, Eq. (1) describes the relaxation of the longitudinal magnetization ($\sim \tau_m^{-1}$) as well as the relaxation of longitudinal chain vibrations due to frictions with the solvent ($\sim \psi$). In Eq. (1) ρ_f is the equilibrium density of chained ferrofluid particles and χ is the phenomenological chain rigidity modulus [5]. If the damping is sufficiently small and/or the reversible part in Eq. (1) sufficiently large, one expects from Eq. (1) a propagating magnetoelastic soundlike mode with velocity $m_0(\chi/\rho_f)^{1/2}$, where m_0 is the static magnetization due to the external field $\mathbf{H}$.

While this slow mode has apparently not yet been observed in ferrofluids, we strongly believe that the slow mode reported in Ref. [1] is its analogue for magneto-rheological fluids. Naturally the relevant intrinsic relaxation frequencies are not several MHz as for ferrofluids, but rather $\sim 10^2 \ldots 10^3 Hz$ due to the larger particles involved. This allows the mode (1) to be propagating even at rather large wave lengths. The observed peak shifts and the amplitude changes with field are compatible with the macroscopic description of the proposed mode.

The physical picture presented here leads to a number of experimentally relevant points: The wave velocity is growing with growing magnetic field, for $k_z \to 0$ no propagation is possible, but only pure relaxation, and there is no propagating slow mode in the planes perpendicular to the directions of the columnar structures. These features seem to be compatible with the present experiments [1,3]. To summerize, we have pointed out why the experimental results described in [1,3] are incompatible with the compressional wave expected for a fluid-saturated porous medium [2,4]. We have proposed a different physical mechanism for the slow mode observed in Ref. [1].

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